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3D VOLUMETRIC DISPLAY STUDY

Clyde Flackbert, et al

Motorola, Incorporated

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MOTOROLA INC.
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3D VOLUMETRIC DISPLAY STUDY
FINAL REPORT

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Approved By: J. Pendleton

J. Pendleton, Manager
Display Section

Approved By: R. Yost

R. Yost, Chief Engineer
Radar Engineering Department

By
Motorola Inc.
Government Electronics Division
Scottsdale, Arizona

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FOREWORD

This report was prepared by Motorola Incorporated, Government Electronics Division in conjunction with Battelle's Columbus Laboratories, under Contract N00014-72-C-0180, ONR Task No. NR215-196. Mr. Carl M. Verber served as principle investigator for Battelle Columbus Laboratories and Messrs. Clyde Flackbert and Fred Keiner for Motorola Inc.

SECTION 1

1. INTRODUCTION

The increasing sensitivity, resolution and range capabilities of electronic sensors such as radar, infrared, sonar, and EMW, are providing vastly improved target signature data leading to the more effective detection, recognition, and identification of targets of interest. To be useful, sensor data must be assimilated, essential data extracted from nonessential data, management decisions made and actions initiated — all in a timely fashion. This process requires that electronic sensor information be reduced into its essentials and be displayed rapidly and accurately to the equipment operator and system manager on an interactive basis. Machine-man-machine communications must be concise and be accurate to optimize mission effectiveness. The 3-D visual display represents a potential solution to the problem.

A new technique for implementing a true 3-D volumetric display was independently invented by Battelle Memorial Institute in 1970. The Battelle Development Corporation has submitted a patent application covering the entire three dimensional display system. During the course of the work on the patent application, several examples of relevant prior art were discovered. In particular, patent No. 3,123,711, issued to Jack Fajans on March 3, 1964, discribes a luminous spot display device. This patent is now assigned to the Battelle Development Corporation. The Battelle technique employs two beams of electromagnetic energy intersecting at a point in space. (These beams either will be in the invisible regions of the spectrum or will be rendered invisible through the use of appropriate filters). When this is accomplished in the proper medium, visible fluorescence results at the beam intersection. The net result is a capability for creating "points of light" in three-dimensional space. The basic property of Sequentially Excited Fluorescence (SEF) in a medium was confirmed by laboratory experiments conducted by Battelle. Subsequent research revealed potential implementations as well as needed areas of exploration. As a result Motorola and Battelle Columbus Laboratories formed a team early in 1970 to integrate the ultimate display, thereby adding development and implementation expertise to basic research capabilities.

A proposal to study the basic SEF concept was prepared by Motorola and submitted to ONR on Sept 1, 1971. The effort was considered by ONR to be the beginning of a series of programs eventially leading to the development of a true volumetric 3D display. This study program resulted in the initial ONR investigative effort. The intention of this effort was to uncover the areas needing development emphasis based on technology trends. With such information at hand, an orderly plan can be developed predicting the essential construction of prototype hardware.

During the course of this study an attempt has been made to gather information relating to basic volumetric display system elements — energy sources, deflectors, and display media.

Because of the extensive work accomplished to date, and the applicability of existing technology, the display system architecture is not considered a critical area and was not addressed in this study. The study first derives the display performance equations, and then considers the display media, the energy sources, and the deflectors. Also included is a description of specific requirements for various classes of potential displays, and a time phased plan for their realization.

What should be done next? Two avenues deserve immediate attention. The first is to study materials which have the potential for a higher operating efficiency (conversion of pump energy to useful output) than the present display media. Such a program should concentrate on gaseous display media for the following reasons:

1. Ease of fabrication of large volumes. This will be facilitated by using a buffer gas to keep the display volume at atmospheric pressure.

2. Avoidance of optical problems caused by an index of refraction mis-match. This is particularly important for multiple vantage point viewing.

3. Preliminary calculations indicate the possibility of high conversion efficiency.

It is anticipated that the end result of this program will be the identification and characterization of a gas suitable for a small display of several thousand spots when excited by one watt lasers. In the past, almost all work on gases for the SEF display has been theoretical. The first result of such work was the identification of the range of parameters to describe a gas suitable for a high performance display. Stated briefly, the gas should have a density of 10^{15} molecules/cm^3, or greater, at the operating temperature of the display; it should have a ground state absorption linewidth and oscillator strength consistent with an absorption length of tens of centimeters at the operating density; and it should have an excited state absorption length of several millimeters. A theoretical effort devoted to an estimate of the display capabilities of gaseous diatomic iodine indicated that I_2 should be capable of supporting a moderate display (several hundred spots or more) and that ICl (one of several potentially useful heteronuclear halogen molecules) should be capable of supporting a high performance display (several thousand spots). To date, experimental work with the halogen molecules has been limited to preliminary absorption spectroscopy and resonance excitation of visible flourscence with a tunable dye laser. The second need is to evaluate 3-D display applications and related human factors requirements. In the development of any new display system, it is important to determine, as early as possible, the man-machine parameters inherent in the system. Generally, these parameters are concerned with operator functions such as detection and tracking, discernment of patterns, and perception of spatial relationships. To obtain data on such parameters, it is conventional to construct a laboratory model of the display system and conduct human factors tests, as required, to yield the requisite information. Motorola has proposed a program to satisfy this need. As proposed, Phase 1 is an exploration of military applications for volumetric display and Phase 2 is a human factors evaluation using the data base obtained during Phase 1.

SECTION 2

2. THREE-DIMENSIONAL TECHNIQUES, APPLICATIONS, AND HUMAN FACTORS

2.1 THREE-DIMENSIONAL TECHNIQUES AND POTENTIAL APPLICATIONS.

"Man possesses a highly refined and well practiced sense of depth perception which is not used when viewing a conventional 2-D display. If a third dimension is added to a display, system capacity is increased."[1]

The ideal 3-D display offers the possiblity of presenting complex and/or fast changing data to an operator in a fashion that enhances the operator's ability to interpret such data and to perform resultant management decisions. In the ideal sense a 3-D display also would render 2-D data portrayals where projections along selected axes are desirable. This property is vital if the operator's task requires more than a subjective examination of 3-D data.

At present, four general approaches to the problem of presenting multidimensional information are distinguishable: coding in 2-D presentations, perspective and other monocular in 2-D presentation, stereoscopic 2-D systems, and volumetric (3-D) devices. The basic characteristics of each are briefly summarized as follows:

2.1.1 Coding

Coding techniques indicate a third-dimension on a two-dimensional surface by graphical, numerical, color, or alphabetic symbology. Various schemes have been evaluated over the years and many are presently in use. A typical example is the range-height display used to supplement plan position indicators in ground control approach radars. Also supplemental alpha-numeric data blocks may be placed on a 2-D display to indicate a third dimension (aircraft altitude for example). This display technique is adequate for many applications but suffers the serious disadvantage of display clutter when coding is applied to more than a few targets at any one time. Dual 2-D presentations have the disadvantage of poor target correlation if there are more than a very few targets on the display at any one time. In general, it may be stated that coding is a restrictive system of adding additional information to a display; it is best applied on an individual target basis or upon request of the equipment operator.

2.1.2 Perspective and other Monocular Cues

A pseudo 3-D effect can be obtained by using monocular cues such as size, perspective, or shading to produce the illusion of depth on a 2-D surface. Examples are the display of an

object as an isometric projection, the use of a trapezoid to represent a runway, simultaneous modulation in the Y and Z axis to produce a bas-relief effect on a CRT, etc. While displays of this nature indicate the presence of a third dimension, the indication is based on the view from a single vantage point and the measurement of depth is not readily available to an operator. Coding is required to measure depth. The restrictions of coding as described in the previous paragraph apply to this technique. However, a major advantage of this technique is that both inside-out and outside-in viewing can be portrayed to the observer.

2.1.3 Stereoscopic Systems

Stereoscopic viewing of separate 2-D displays, one for each eye, employs the use of binocular disparity as an additional optical cue to enhance the illusion of 3-D. Stereo viewing has been evaluated for many years from both the device and human factors standpoint. While this technique offers a realistic illusion of depth, it generally suffers the basic deficiencies of single vantage point viewing and the wearing of special viewing devices. Recent computer-generated displays have somewhat relieved the constraint of single vantage point viewing by measuring the position and attitude of the observer's head and changing the displayed object accordingly. At present, computer generated displays of this nature are confined to "outline drawings" of simple objects such as cubes, Lissajous patterns, spirals, etc. The elimination of "hidden" lines and generation of complex surfaces both remain difficult problems. Additional difficulties associated with stereoscopic viewing are the fact that not all observers can accommodate this type of display. For some, eye strain results and for others the illusion of depth is not evident. A further difficulty is the fact that depth measurements are not self evident - - that is, some form of "depth coding" must be employed to assist in measurement.

Again, a major advantage is the feasibility of "inside-out" viewing, in which the observer seems to be inside the displayed volume.

2.1.4 Volumetric Devices

A volumetric display is the only technique that presents depth in a real rather than a synthetic fashion. Thus, all of the optical cues are employed; that is, binocular disparity, perspective, size, and focus. Viewing in the "depth" axis is more easily accomplished. Also, simultaneous viewing from multiple vantage points is inherent in the volumetric display.

2.1.5 Summary

Much remains to be investigated in the field of volumetric displays. The fact that data displayed by light emitting points is "transparent" must be considered, although preliminary experiments have indicated that this will not lead to perception problems. Display size, inside-out, and outside-in viewing are likewise basic considerations.

Perhaps the greatest single advantage of a volumetric display is the possiblity of communicating a "whole picture". As such, it appears a major use could be as a supervisory display, i.e., a display useful to a group - - a display that would provide an overview of a situation for high level command decisions. Situations of this nature characteristically involve a multiplicity of complex data with the requirement of fast and accurate management decision making. Applied to a tactical situation, a volumetric display could enable a commander to view an overall aerial, surface, and undersea situation in a single display with the freedom to change his view point at will.

2.2 POTENTIAL APPLICATIONS

The following are examples of possible applications for 3-D displays:

2.2.1 Ships; Surface, and Submersible: (Sonar coupled and radar coupled sensors)

- Combat Information Center: Unified presentation of air, surface, and submarine forces.

- Supervisory Obstruction Avoidance: 3-D portrayal of ice packs; bottom topography.

- Fire-Control: Assignment of AAA batteries and missiles to specific targets or threat sectors.

- Air traffic control: Supervisory.

- Target Recognition and/or Identification: Form recognition under conditions of unfamiliar size and distance is enhanced by a 3-D presentation. Target signature cue combinations such as range, bearing, shape, and spectra, presented in a 3-D form, may well serve to "organize" the various signature data in a manner to enhance the operator target recognition/identification function.

2.2.2 Aircraft: (Radar coupled)

- Drone Aircraft: Monitor and control of single or multiple drone aircraft particularly at the system management level.

- Station Keeping and Rendezvous: Aircraft refueling, formation flight, and collision avoidance are representative of fast changing situations amenable to display by 3-D techniques.

- Fire Control and Weapons Management: The guidance and monitoring of air-to-air and air-to-ground weaponry is a possible use for 3-D displays.

2.2.3 Signal Processing:

3-D displays offer the possiblity of enhancing the detection of signals in noise by portraying data in a manner so as to best employ the autocorrelation properties of human binocular vision.

2.3 HUMAN FACTORS CONSIDERATIONS

Of the four general approaches to the problem of presenting 3-D information, the volumetric and stereoscopic 2-D displays most nearly approach the ideal. The volumetric display frees the observer from encumbrance, and provides a natural view to a large number of observers. Against these advantages must be counted the transparency factor and the possible limitation to an "outside-in" view. The stereoscopic 2-D display, in principle, can overcome these disadvantages by presenting a wide-angle view to each eye separately and causing the views to change naturally with head movement. This presently implies objectionable observer encumbrances. Fundamental human factors evaluation material relating to 3-D volumetric displays is as follows:

- Inside-out vs Outside-in viewing.
- Transparency of data.
- Multiple vantage point viewing.
- 2-D data projections of 3-D data.
- Number of data points required.
- Measurement accuracy (in 3 dimensions); cursor considerations.

Each of the preceding are related to operational requirements associated with the various display applications. A human factors study in conjunction with an applications study is required to evaluate man-machine relations pertinent to 3-D volumetric displays.

REFERENCES

[1] Leibowitz and Sulzer, "An Evaluation of Three-Dimensional Displays", Contract No. NONR 2300 (05), 1965, AD No. 457849.

SECTION 3

3. DEVELOPMENT OF A MATHEMATICAL MODEL OF THE DISPLAY

3-1. MATHEMATICAL MODEL

This section is concerned with the development of a mathematical model of the display, starting with the solution of the physical problem of the sequential excitation of flourescence. It has proven convenient to discuss the display in terms of the number of flourescent spots M which can be made to appear simultaneoulsy within the display volume. This number is determined in part by the characteristics of the display medium. The total number of addressable locations, or the field of the display, is not so much a function of the material as a function of the deflectors and optics. We will find it possible to describe the display in terms of the following parameters:

M = Number of simultaneously displayed spots.

R = The rate at which the display is refreshed (sec^{-1}).

L = The length of the display along the direction of the ground state pump (cm).

d = The spot diameter (cm).

B = The spot brightness (foot Lamberts).

The physical problem to be solved is depicted in Figure 3-1 which is a generalized three level energy-level diagram showing excitation by the ground and excited state pumps and the various loss mechanisms. In a Battelle Columbus Labs internal report [1], it was shown that the most efficient way to use a given average pump power is in the form of a sequence of two short pulses as shown in Figure 3-2. This mode results in maximum utilization of the excited state pump and therefore the highest overall efficiency, provided the pulse sequence is delivered in a time significantly less than the lifetime of the first excited state. If neither of the pump pulses is sufficiently intense to saturate the electronic system, the solution of the rate equations under the short pulse approximation leads to

$$f_{31} = N\ I_G t_G\ \sigma_{12} I_E t_E\ \sigma_{23}\ \eta_{31} \text{ photons/cm}^3 \text{ per pulse,} \tag{1}$$

for the flourescent output per pulse. The quantity N is the density of potential emitters and η_{31} is the quantum yield for visible flourescence from the emitting level. The remaining quantities are defined in Figures 3-1 and 3-2.

It is more useful to deal with average pump powers than with energy per pulse. This is easily done by defining the pump powers I_{12} and I_{23} in terms of the energy per pulse and the

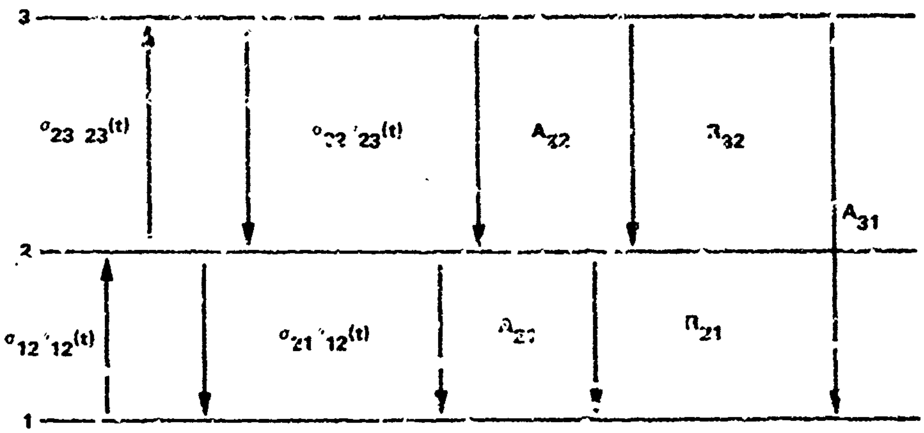

Figure 3-1. Energy Level Diagram

5 55-A

Energy level diagram showing absorption, stimulated emission, nonradiative and radiative decays. Pump intensities are $I_{ij}(t)$, absorption cross sections, σ_{ij}, nonradiative decay rates R_{ji} and radiative decay rates A_{ji}. The desired output at A_{31} occurs at the rate N_3A_{31} photons/cm^3 - sec.

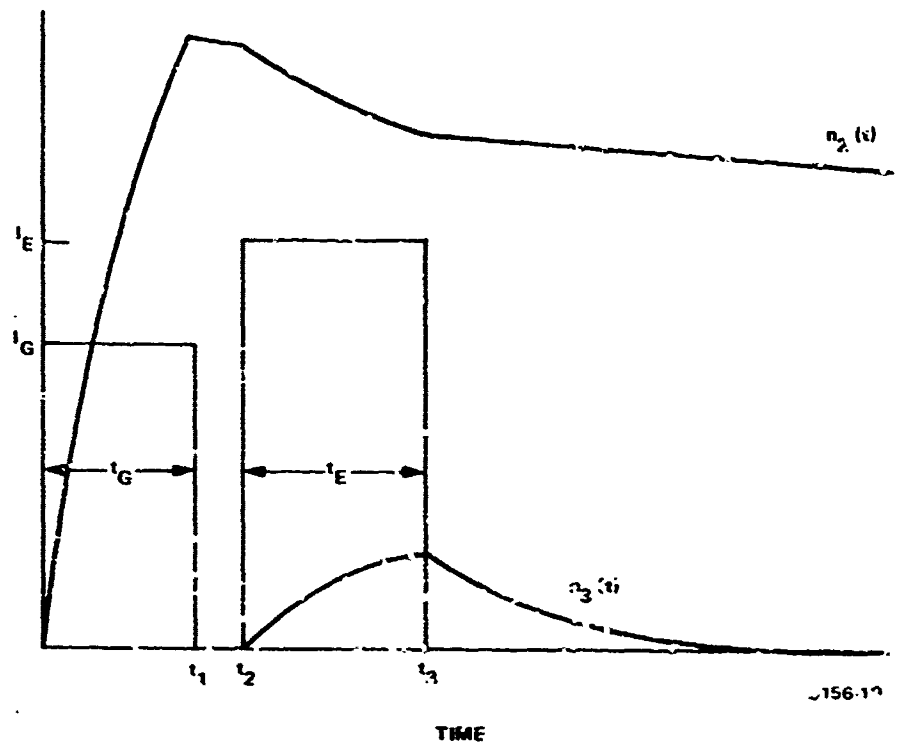

Figure 3-2. Excitation Pulse Pattern

The two excited pulses of intensities I_G and I_E and durations t_G and t_E respectively are shown applied sequentially in a time less than τ_2. The change in population of the first excited state, n_2, and the second excited state, n_3, in response to these pulses indicated.

number of pulses per second. Thus,

$$I_{12} = I_G t_G M R. \tag{2}$$

and

$$I_{23} = I_E t_E M R. \tag{3}$$

Substituting into equation 1 yields

$$F_{31} = R f_{31} = \frac{N I_{12} \sigma_{12} I'_{23} \sigma_{23} \eta_{31}}{M^2 R} \quad \text{photons/cm}^3 \text{ per sec.} \tag{4}$$

The ground state pump must be exponentially attenuated as it traverses the display medium. Therefore, the energy deposited per unit length will reach a minimum at the point in the display fartherest from the point at which this pump beam enters the display. We wish to maximize the excited state population at this point. After traversing a distance x through the display medium the number of centers which a ground state pump pulse will be able to elevate to the first excited state will be

$$N_2(x) = N I_G t_G \sigma_{12} e^{-\sigma_{12} N x}. \tag{5}$$

Maximizing N_2 at the far side of a display of length L yields

$$L = 1/\sigma_{12} N. \tag{6}$$

It should be pointed out that unless the value of N indicated by equation 8 exceeds a certain minimum value, the material in question will probably not be suitable for use in the display. For a given brightness, it is evident that the density of emitters in the upper excited state is given by

$$N_3(\text{min}) = F_{31} \eta_{31}/R. \tag{7}$$

Assuming nonsaturation implies that $N_3 \leq (10)^{-1} N_2 \leq (10)^{-1} N_1$, so we require that

$$N_1 \approx N \geq 100 F_{31} \eta_{31}/R \tag{8}$$

The spot diameter can be included as an explicit parameter by defining the output flux F'_{31} and the pump fluxes I'_{ij} in terms of the output and input photon densities,

$$F'_{31} = \frac{4}{3} \pi (d/2)^3 F_{31} \text{ photons/sec,} \tag{9}$$

and

$$I'_{ij} = \pi (d/2)^2 I_{ij} \text{ photons/sec.} \tag{10}$$

Substituting Eqs. 8, 9 and 10 into Eq. 4 we get

$$M^2 LRF'_{31} (d/2)^2 = \frac{4}{3} I'_{12} I'_{23} \sigma_{23} \eta_{31} = Z. \tag{11}$$

Here, the equation has been separated into parameters which describe the quality of the display and parameters which describe the light sources and the display medium. The constant Z, therefore, represents a measure of the quality of the display, and at the same time a measure of the difficulty of achieving the materials and light sources to construct the display.

As final steps in the development of the system equation, the brightness will be expressed in photometric units using the conversion

$$B = 2.011 \times 10^5 \frac{W(\text{watts})}{d^2 (\text{cm})^2} V_\lambda = 2.011 \times 10^5 \frac{F'_{31} h \nu_{31}}{d^2} V_\lambda \tag{12}$$

and the pump intensities P_{12} and P_{23} will be expressed in terms of watts rather than in photons per second. The final result is

$$\frac{M^2 LRBd^3}{4.022 \times 10^5 h\nu_{31} V_\lambda} = \frac{4}{3} \frac{P_{12} P_{23}}{h^2 \nu_{12} \nu_{23}} \sigma_{23} \eta_{31} = Z \tag{13}$$

where V_λ is the visual spectral sensitivity coefficient which is unity at the sensitivity peak (0.55 μ) and falls to zero in the IR and UV regions of the spectrum.

3-2. A PROPOSED DISPLAY HIERARCHY

Having developed an expression by which a given display can be characterized, it is now possible to tabulate the properties of a proposed hierarchy of displays and calculate the characteristic parameter Z which is a measure of the difficulty of constructing each of these displays. This is done in Table 3-1. To reduce the number of variables in Table 3-1, it was assumed that all of the displays had green ($\lambda_{31} = 0.56\ \mu$) outputs. Thus

$$V_\lambda = 1$$

and $$\nu_{31} = 5.4 \times 10^{14}\ H_2$$

The lowest order display described in Table 3-1 is the bench model which Battelle Columbus Laboratories plans to construct for the Air Force Avionics Laboratory. The most advanced display is the ONR goal which was discussed in Motorola's proposal to ONR resulting in the current project. As can be seen, the Z values for these two displays differ by some nine orders of magnitude. In the following section equation 13 will be discussed in terms of some specific material parameters. It also will be shown that it is reasonable to span this range of Z with improved display materials.

3.3 SOME OPTICAL LIMITATIONS

In Table 3-1, the display size and the spot size have been kept relatively constant. Equation 13 defines tradeoffs between d, L and the other display parameters. However, these parameters may not be varied without limit. The restrictions stem from the fact that true collimation of a light beam is not possible, and the smaller the minimum beam diameter, the larger the divergence. The specific L to d ratio achievable is a function of a number of parameters including initial laser beam diameter and beam quality, the tolerable spot variation and the focal length of the lens which is used. For example, it can be shown that for a 2mm difraction limited laser beam, a 1 meter focal length lens will produce a beam of 0.5 mm diameter which will vary by no more than 10% over a 20 cm path length [2]. The achievable L/d is, in this case, 400.

The L/d values for the four displays in the proposed hierarchy are given in Table 3-1. These values as well as the time per event are also relevant to deflector characteristics and will be referred to again in the discussion of deflectors.

Table 3-1. Display Hierarchy (assuming green output)

		Bench Test	First Interim	Second Interim	ONR Goal
Number of spots	M	10	500	5000	50,000
Length (cm)	L	10	15	15	13
Refresh rate $(sec)^{-1}$	R	20	30	30	30
Brightness (ft Lamberts)	B	1	2	30	30
Spot diameter (cm)	d	.05	.05	.05	.05
Characteristic parameter	Z	1.6×10^{13}	1.9×10^{17}	2.8×10^{20}	2.4×10^{22}
Spots per axis	L/d	200	300	300	260
Time per event (μ sec)	$(MR)^{-1}$	5000	67	6.7	0.67

REFERENCES

[1] Verber, C. M. and Jones, W. H., "Theory of the True 3-D Display", Internal Report, Battelle Columbus Labs, 1970.

[2] Dickson and Cecchi, "Electrical-Optical System Design", p. 20, Nov. 1970.

SECTION 4

4. THE DISPLAY MEDIUM

4.1 CRITERIA OF A GOOD DISPLAY MEDIUM

The function of the display medium is to convert the energy of the pump beams into fluorescence at a wavelength different from either incident beam. In order to produce sufficient intensity, the density of the active centers must exceed a minimum value. The minimum value is a function of the required brightness, the refresh rate and the intrinsic conversion efficiency of the material. In addition, the lifetime of the first excited state must exceed a certain minimum value so that there is no difficulty in timing the excitation pulses, and yet this lifetime must be short enough so that no unwanted spots are formed.[1] These unwanted spots, or ghosts, occur when the ground state pump beam intercepts the path of the excited state pump which has not yet had time to decay. In some materials, and particularly in gases, this phenomenon can be controlled to some extent by introducing quenching materials so that the life time of the metastable state can be controlled to lie within a suitable range. In a liquid or gas, the fluorescence lifetime should be short enough to prevent diffusion of the fluorescing spot. In addition, neither of the exciting beams should be able to excite the desired fluorescence without the cooperative action of the other beam.

A number of additional criteria relating to the use of potential materials in the actual display must be kept in mind. For example, materials which present apparently unsolvable containment problems or unusually difficult preparation problems should not be considered.

In Figure 4-1 the interaction of an ideal display material with the pump beam is depicted. The ground state pump, entering from the left, is attenuated exponentially as it traverses the display volume. The attenuation coefficient can be adjusted by appropriately choosing the concentration of absorbers. It has been shown that the optimum absorption length is the x-dimension of the display.

The excited state beam, entering from the bottom, traverses the display with no attenuation until it intersects the region previously traversed by the ground state pump. As shown, it then suffers severe attenuation in the prepumped region. Achieving this behaviour in a real material requires ground state and excited state absorption cross sections which differ in many orders of magnitude.

4.2 POTENTIAL DISPLAY MEDIA

The following discussion deals with specific classes of materials which have been considered as display media. Specific possibilities are identified and an attempt has been made to predict the performance expected of these materials and to indicate preferred research paths.

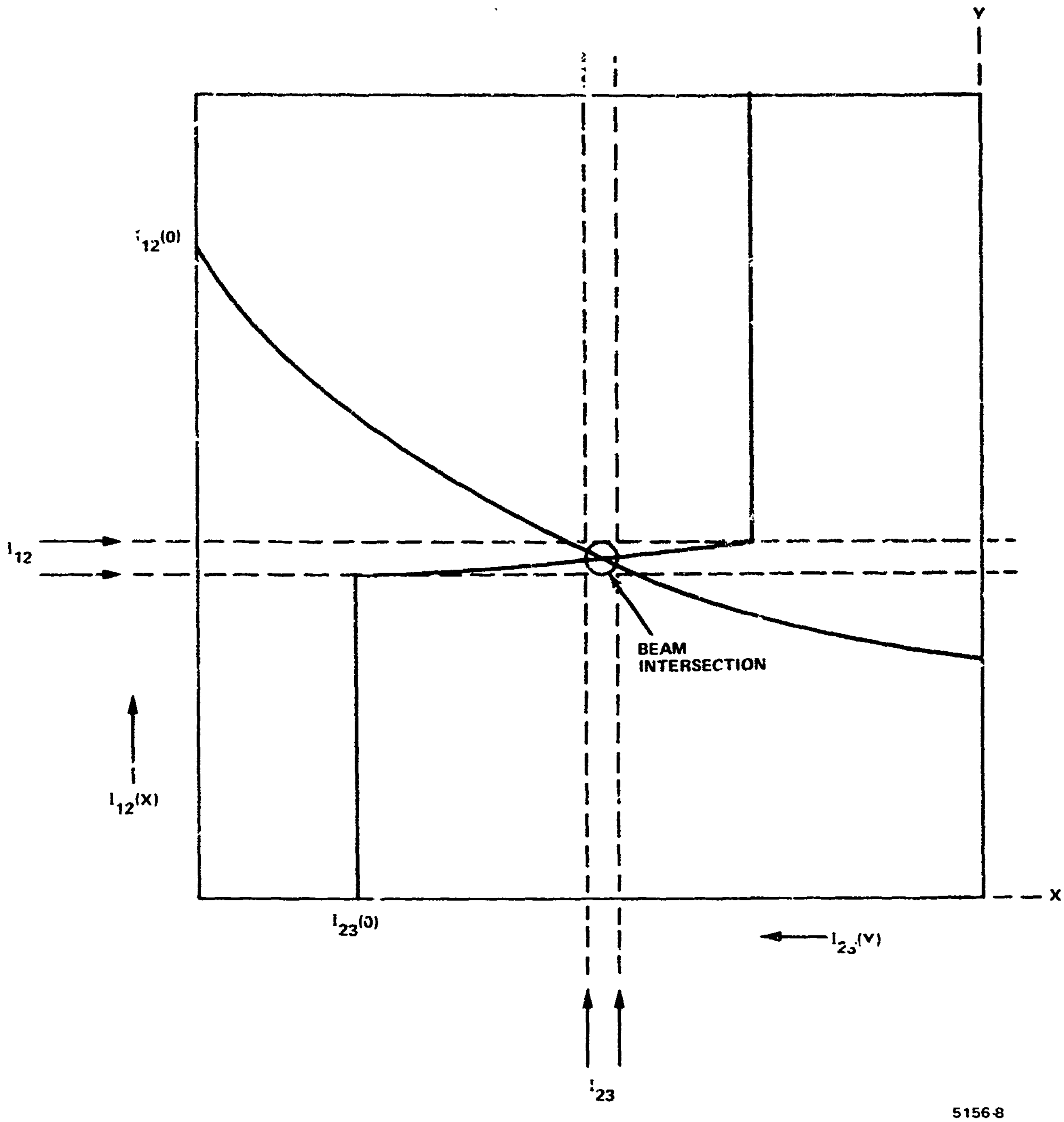

Figure 4-1. Interaction of the Pump Beams With an Ideal Material

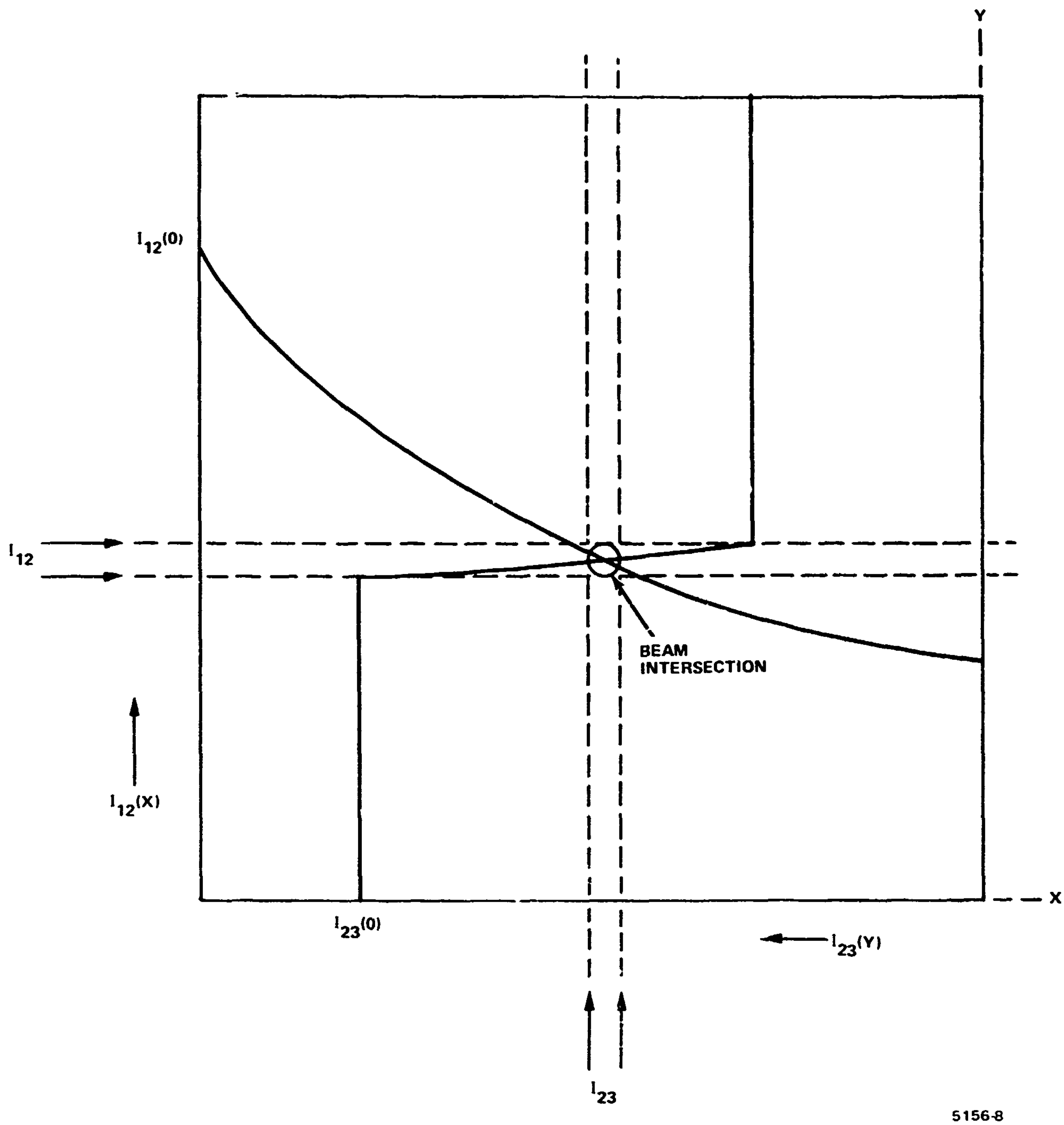

Figure 4-1. Interaction of the Pump Beams With an Ideal Material

4.2.1 Trivalent Rare-Earth Ions

Trivalent rare-earth ions present as dopants in various solid matrices were selected by Battelle as the first materials for study. The basis for this choice was that a significant amount of work on the use of these materials as infrared quantum counters had been done and that the quantum counter and SEF mechanisms are basically the same.

The result of the work on the trivalent rare-earth ions was that a number of possible display schemes were identified and characterized. It was realized during the course of this work that the efficiency of these materials in converting the energy of the pumping beams to the desired visible fluorescence was very low. This low efficiency is due entirely to the fact that the transition between the first and second excited states is a forbidden transition and therefore results in a very inefficient utilization of the excited state pump. There are two possible approaches to improving the situation with the trivalent rare earths. The first of these, which has been pursued to some extent by workers at the RIAS laboratory of Martin-Marietta, is the control of the conditions under which the crystals are grown in such a way as to minimize the number of crystallographically different sites in which the rare earth ions find themselves. This is expected to result in narrower absorption lines and a consequent increase in the absorption coefficient for the excited state pump. However, these efforts are not expected to produce more than an order of magnitude increase in the excited state absorption cross-section. A second approach which also is directed toward improving material characterization by controlling the local environment around the rare earth ions is to use host materials other than the fluorides which have been used to date. Experiments at the Battelle Columbus Laboratory with Y_2O_3 host powders have shown the potential of a factor of 2 or 3 improvement over the CaF_2 host. Neither of these properties seem to have a sufficient payoff to warrant an extensive research program.

4.2.2 Divalent Rare-Earth Ions

The infrared and visible transitions of the trivalent rare-earths are due to normally forbidden transitions between levels of the $4f^n$ configuration. They usually are made possible by crystal field admixture of components of opposite parity in the wave functions and have oscillator strengths in the order of 10^{-6}. Allowed transitions do not occur until ultraviolet energies are reached. On the other hand, in the divalent rare-earths, the energy difference between the bottom of the $4f^{n-1}$ 5d and $4f^n$ configurations spans a range varying from the infrared through the visible and into the ultraviolet. There is, therefore, a possibility of finding a divalent RE ion with a forbidden ground state absorption and an allowed excited state absorption. This is the ideal combination for the SEF display. For these reasons some effort was spent in the investigation of the divalent rare earth ions.

It was found that of the fourteen rare earths, only 4 of the divalent ions fluoresce in the visible region of the spectrum. These are Sm^{2+}, Eu^{2+}, Tm^{2+} and Yb^{2+}. Neither Eu^{2+} nor Yb^{2+} have an infrared metastable level which would be suitable for use as the first excited state in the SEF scheme. Tm^{2+} is the only divalent rare-earth ion in which quantum counter or SEF action has been demonstrated. As was expected, due to the allowed excited state

transition, its quantum efficiency was some 3 orders of magnitude higher than that exhibited by the trivalent ions. However, the output wavelength in the material investigated ($SrCl_2$: Tm^{2+}) was 0.72μ which is too far into the infrared region to be useful in a display system.

The work on the $SrCl_2:Tm^{2+}$ system was performed at RCA during 1960 under a contract from the U.S. Army Engineer Research and Development Laboratories. This work is described in detail in a series of reports which do not contain any information suggesting any modification of this system to make it a suitable display medium. The most discouraging facts are that the host is not easily prepared in large single crystals and that the mechanism of the fluorescence is not understood. This means there is no rational basis to search for hosts which might push the fluorescence wavelength further into the visible.

The potential of Sm^{2+} is not clear, and deserves some additional attention. It is known that Sm^{2+} has 4f $\rightarrow$ 4f absorptions at 2.47μ and 4.37μ.[1] These lines are relatively narrow ($\sim$20A) and have oscillator strength of $\sim 3 \times 10^{-7}$. They have been observed in CaF_2, but because they are 4f $\rightarrow$4f transitions they should be relatively insensitive to the particular host used. There is no data available on the lifetime, or even the spectroscopic labeling of those levels. An additional line is predicted at 3.1μ but has not been observed. If this line is present, we can expect in most hosts a multiphonon decay of the 2.47μ level to the 3.1μ level. This will limit the lifetime of the 2.47μ level to less than 10^{-5} sec. If the 3.1μ level does not exist, the 2.47μ lifetime probably will be determined by radiative processes and will be in the millisecond range.

The excited state pump probably will be in the 8000Å range and will pump a transition whose oscillator strength is expected to be about 10^{-2}.

It is anticipated that the Stokes shift will be such that the fluorescence will occur at a wavelength sufficiently longer than the red end of the absorption band and that no reabsorption will occur. This should be verified experimentally.

The situation with respect to the output wavelength of Sm^{2+} is not clear. In CaF_2, there is a large body of experimental data which indicates that the fluorescence peaks at 7100Å for low temperatures and shifts towards the infrared as the temperature increases. The room temperature fluorescence peak is about 7500Å, which is clearly unsuitable for the display. However, according to Pringsheim,[2] Sm^{2+} fluoresces at 6200Å for which $V_\lambda = 0.38$. This would be a perfectly suitable wavelength, but Pringsheim's book is not clear which host material results in this fluorescence wavelength, although it is probably one of the alkali halides. It is currently felt that the Sm^{2+} ion offers the only worthwhile possibility for use as a display material among the RE^{2+} ions. However, no definite conclusions can be drawn without further investigations.

4.2.3 Other Solid Display Media

It is known that a number of other ions, particularly those in the 3d period, fluoresce in various solid matrices. However, no reasonable SEF scheme was found for these ions and

no experimental display work has been done on them. An article by M. R. Brown and W. A. Shand discussed these ions but presented no hope for their use in the SEF display.[3]

4.2.4 Organic Molecules

Organic molecules offer certain clear advantages in any device application. Sufficiently small changes can be made in molecular structure to provide virtually a continuum of properties within a range reasonable for organics. The organic modules are convenient for gas phase work since their vapor pressures are high when compared with that of inorganic species of similar molecular weight. This is a consequence of weak bonding in organic molecular crystals versus the bonding in covalent or ionic crystals.

The spectral properties of organic molecules can be described in terms of the generic energy level diagram of Figure 4-2. The $S_0 \rightleftarrows S_1 \rightleftarrows S_2$ and $T_1 \rightleftarrows T_2$ transitions are allowed. The $S_1 \rightarrow S_0$ decay usually is responsible for fluorescence. This is because nonradiative decays within the singlet manifold and intersystem crossing from the triplet to singlet levels depopulate all but the S_1 and T_1 levels. The $T_1 \rightarrow S_0$ decay and $S_1 \rightarrow S_0$ decay both can produce visible radiation. However, since almost any excitation of the molecule results in these outputs, they are not suitable outputs for an SEF scheme. Only one case of $S_2 \rightarrow S_1$ flourescence has been reported (in the azulene compounds), however, no reasonable SEF scheme exists.

The only other viable scheme for utilizing organic molecules is to use the $T_2 \rightarrow T_1$ fluorescence. This has been observed in rubrene. Two excitation schemes are possible, both using the T_1 level as the metastable state. This can be populated by direct $S_0 \rightarrow T_1$ absorption or by the addition of a sensitizer to the molecule. As shown in the figure, the second step is a $T_1 \rightarrow T_2$ absorption. By virtue of nonradiative decay in the T_2 manifold the $T_2 \rightarrow T_1$ emission is separated from the pump wavelength by several hundred angstroms. This system should be investigated.

4.2.5 Monatomic Gases

Because of their superior optical quality, ease of preparation, and reduced cost, it became evident that gases were to be preferred over solids or liquids as the ultimate display medium. In addition, each of the spectroscopic characteristics required of a superior display medium are individually realized in many gases. Careful analysis and consultation with a number of eminent spectroscopists (most extensively with H. Broida, Univ. of California and K. N. Rao, Ohio State Univ.) resulted in the conviction that there was no intrinsic prohibition against these characteristics existing in the proper combination in a single gas. Since there was virtually no coherent background of literature on excited state excitation mechanisms in gases allowing for characterization of SEF efficiencies, with a screening process was initiated. This screening process was designed to eliminate from further consideration those gases shown to be unsuitable on the basis of other well know properties. This screening process utilized as basic criteria the density of the gas at reasonable temperatures, the energy of the first excited state, and the presence of visible fluorescence.

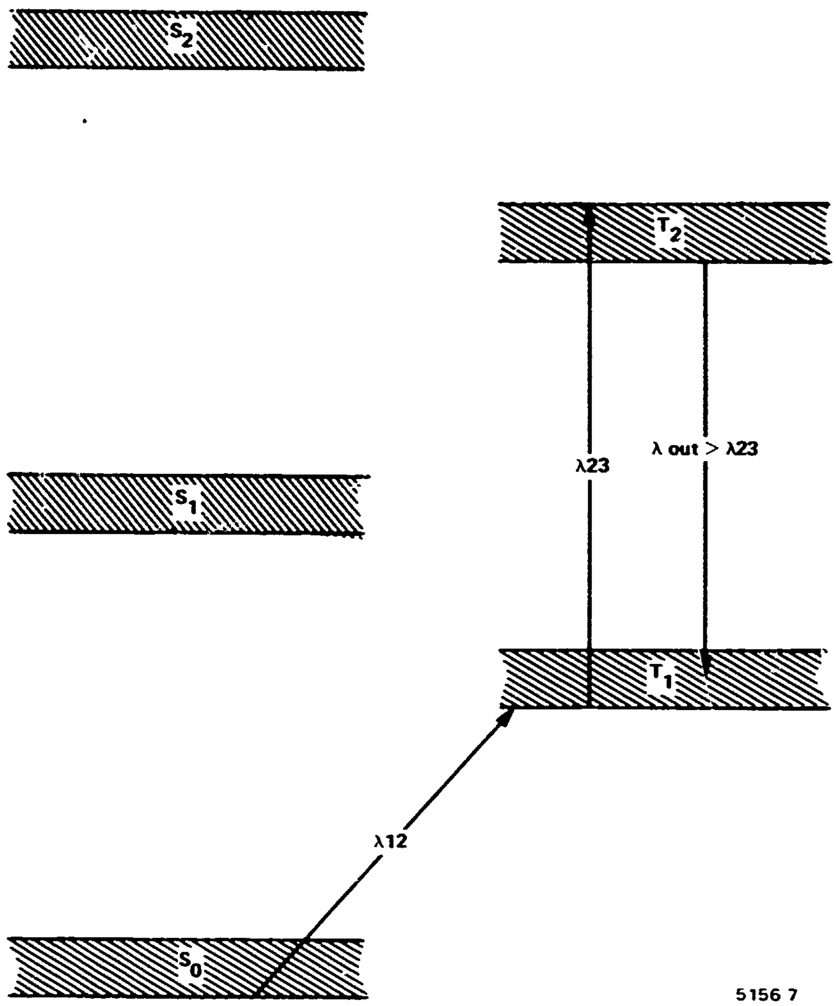

Figure 4-2. Typical Organic Module Singlet and Triplet Manifolds

Diagram of the singlet and triplet manifolds of a typical organic molecule showing the SEF scheme suggested for rubrene. The width of the electronic levels is due to a vibrational and rotational substructure which is not shown explicitly.

Among the monatomic vapors, the minimum density criteria eliminated all but the noble gases and Hg. The noble gases have their first excited state in the vacuum ultraviolet region and must therefore be discarded since no corresponding lasers exist. Na, K, Rb, and Cs have similar chemical and spectroscopic properties. Based on several arguments all may be eliminated from consideration. First of all, temperatures on the order of 500°K are required to reach the necessary density. Since these elements are highly reactive, the elevated temperatures are expected to result in severe containment problems. Furthermore, sodium is the only member of this group with a bright visible fluorescence. Since this fluorescence originates from the first excited state, severe single beam excitation problems are likely. Consideration of the sodium energy level diagram reveals no promising SEF scheme.

Mercury is the only remaining monatomic vapor. It previously had been dropped from consideration for a number of reasons. The most notable fact is that its lowest excited state, 6^3P_0, lies 2656Å above the ground state and is therefore well beyond the range of available lasers. However, the advent of a tunable dye laser with a short wavelength limit of 2650Å (Chromatix Model 1050) makes it advisable to reconsider this material.

The vapor pressure of mercury is such that the minimum required density is exceeded at 30°C. The spectroscopy is exceedingly well known, and the formation of a visible spot by the SEF process was demonstrated in 1963.[4] The excitation scheme used is illustrated in Figure 4-3. The 2537Å line excites the atom from the 6^1S_0 ground state to the 6^3P_1 excited state. A collisional deexcitation to the metastable 6^3P_0 level then occurs, followed by the second excitation with 4047Å radiation exciting the atom to the 7^3S_1 level. The output at 5461Å accompanies the decay to the 6^3P_2 level. Zito and Schraeder report a conversion efficiency for this scheme which is several orders of magnitude better than we have obtained with the rare-earth ions. This is due to the fact that the $6^3P_0 \rightarrow 7^3S_1$ transition is highly allowed.

Our initial calculations indicated an absorption length of less than 0.2 cm for the 2537Å pump at room temperature. Efficient pumping of a reasonable volume is possible only by utilizing the wings of the absorption line, the approach used by Zito. A better approach might be to populate the 6^3P_0 level directly, since the $6^1S_0 \rightarrow 6^3P_0$ transition at 2656Å is weaker than the $6^1S_0 \rightarrow 6^3P_1$. Unlike the 2537Å line, it has the additional advantage of lying within the range of the Chromatix laser. We have not been able to find a value for the strength of this transition in the literature reviewed to date but we have not yet made a complete search.

There are a number of difficulties associated with the use of atomic mercury as a display medium. The most obvious problems result from very narrow absorption linewidths ($\sim 5 \times 10^9$ Hz or 10^{-2}Å at room temperature). This means that a spectrally very narrow pump beam with a high degree of stability must be used. The use of a spectrally broader pump would, of course, result in inefficiencies since most of the pump energy would lie outside the absorption line. Dye lasers of the required stability and linewidth do exist at longer wavelengths, but not yet at the u.v. wavelength required by mercury.

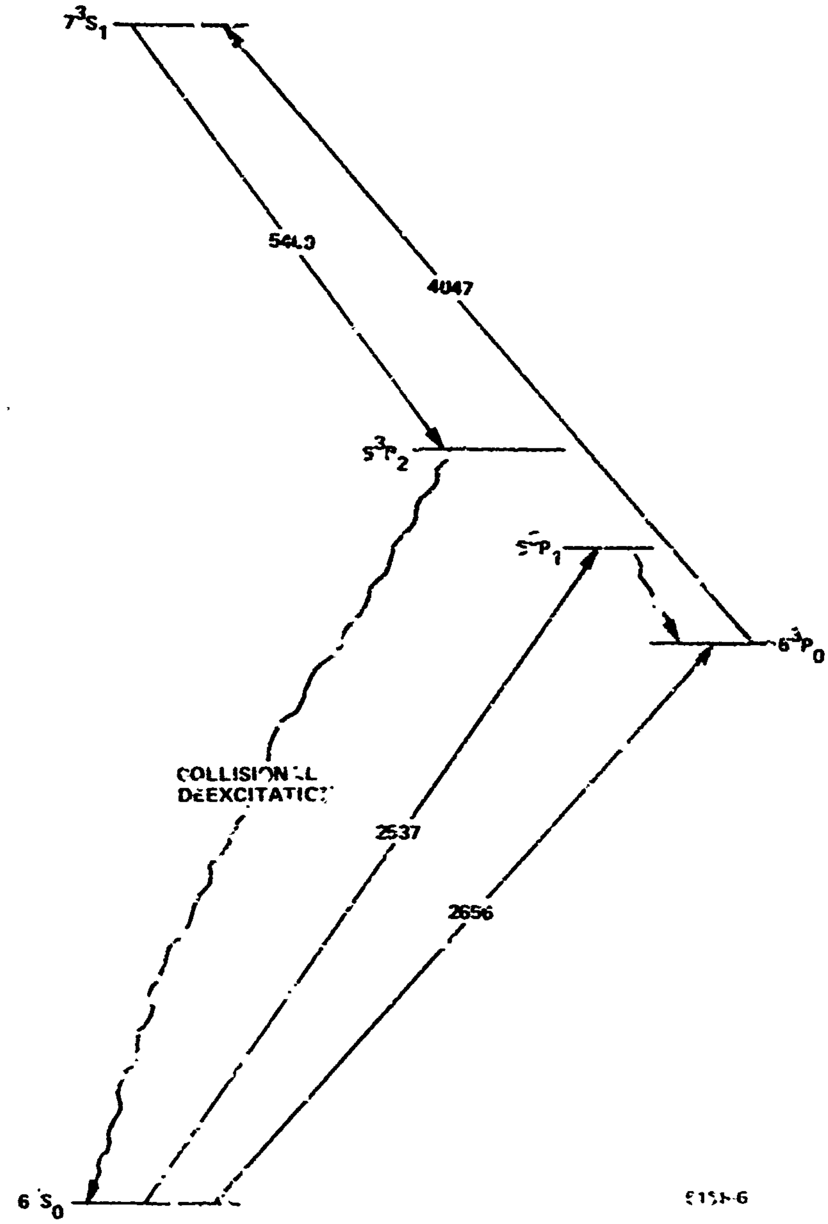

Figure 4-3. Partial Energy Levels of Atomic Mercury

Another potential problem with mercury is the possibility of the photochemical formation of dimers with an attendent emission of visible radiation. Selection of a suitable buffer gas probably will minimize this problem. The basic questions to be answered in the evaluation of mercury as an SEF display medium are; Can the 6^3P_0 level be populated directly, and what is the proper buffer gas. The major experimental problem is expected to be the construction of a suitable ultraviolet pump. At 2537Å, Hg lamps probably will have to be used. At 2656Å the only commercial source is the $40,000 Chromatix dye laser. It may be possible to construct a less expensive laser. Because of the very narrow linewidths, thermal sources are not expected to be useful even for experimental work.

4.2.6 Diatomic Gases

The paucity of suitable monatomic gases led us to extend the search for 3D display media to the diatomics. The same sort of screening procedure was used, and a number of potential display media have been identified. An immediate advantage of the diatomics is that the vibrational and rotational degrees of freedom add sufficient effective width to the electronic transitions significantly reducing the laser problem.

The groups of diatomic molecules which were originally considered were:

- Diatomic halogens, Br_2, I_2, Cl_2, and F_2
- Diatomic mixed halogens such as ICl, IBr, and ClF
- Diatomic alkali metals, Cs_2, Rb_2, K_2, and Na_2
- Diatomic mixed alkali metals such as CsRb and NaK
- Diatomic mercury, Hg_2, and mercury alkali metal diatomics such as CsHg, RbHg, and KHg
- Diatomic S_2, Se_2, and Te_2
- Diatomic N_2, H_2, O_2, CO, and NO.

Because of ease of handling, chemical stability, availability and known visible fluorescences, the diatomic halogens were selected for initial study. The iodine molecule was chosen for the first detailed calculations since its spectroscopy is best known of all the diatomic halogens. It was concluded that, within the limits of reliability set by the estimates of certain unmeasured spectroscopic parameters, the iodine molecule has a high probability of being successfully used as the display medium in a moderate size display. The main drawback of the iodine molecule seemed to be a rather low excited state transition probability. This problem can be alleviated by the subsequent use of a heteronuclear molecule such as ICl.

The results of the calculations and the fact that the I_2 and ICl molecules require pump wavelengths in the infrared region covered by available tunable lasers (e.g., the Chromatix parametric oscillator), indicate that these molecules should be investigated.

4.3 SUMMARY

Solids doped with trivalent rare earth ions are the only materials for which we have complete SEF data. These are relatively poor display materials since the ground and excited state absorptions are forbidden transitions with approximately equal absorption cross-sections. For example, if used with 1 watt lasers, $CaF_2:Er^{3+}$ has a Z-value of 2×10^{16}. The oscillator strength, which is the basic measure of transition probability, is about 10^{-6} for trivalent rare earth. Oscillator strengths of unity are possible and are observed in many materials. Furthermore, the line width of the ionic absorption in solids is on the order of hundreds of Angstrom units. The absorption cross-section is proportional to the line width, and widths of 0.1A are possible in gases. Therefore, 8 or 9 orders of magnitude improvement in material characteristics should be obtainable so that it is reasonable to think of Z values of 10^{22} being exceeded by several orders of magnitude with 1 watt of average pump power.

The possibilities for continued materials research are summarized in Table 4-1. It should be emphasized that in estimating the ultimate performance of the materials listed, appropriate lasers have been assumed.

In making recommendations for the optimum path to follow in continuing the material research program, it is necessary to define specific goals or a set of ground rules to aid in the decision making process. These goals must be established with materials research considered as part of a system development program. Consequently, research priorities must be influenced by the projected availability of compatible components. Therefore, the recommended path may change drastically as the state of knowledge of materials, lasers, and deflectors advances.

A materials research program should be guided by the short range goal of achieving the First Interim Display (500, 2 ft-Lambert spots) while at the same time demonstrating the capacity of the materials to achieve at least the performance level of the Second Interim Display (5000, 30 ft-Lambert spots). It is apparent that the trivalent rare-earths and TM^{2+} should be eliminated from consideration. Mercury, a material in which SEF behavior has been demonstrated, presents severe light source difficulties both for experimental work and for the ultimate display. Therefore, experimental work on mercury should be deferred. However, since the literature on mercury is extensive, a man month of literature work and calculations probably will allow an accurate assessment of the potential of this material. Attention should be paid to estimating the magnitude of deliterious effects resulting from chemical interactions of excited states. After this preliminary study, the decision to pursue an experimental program could be made when light sources become available.

Table 4-1. Summary of Material Research Possibilities

Material	Z * (approximate)	Number of 0.5 mm 30 ft. Lambert Spots *	Probability of Success	Difficulty	Comments
$CaF_2:Er^{3+}$	2×10^{16}	35	Certain	-	Currently available material
Trivalent RE Ions-Host Modification	6×10^{17}	200	High	Moderate	Mainly a crystal growing problem with some spectroscopy
Divalent RE Ions					
Tm^{2+}	1×10^{18}	300	Very Low	High	No obvious approach - not worth pursuing
Sm^{2+}	2×10^{2}	3000-5000	Low	Low	A man month preliminary study is worthwhile
Organic Molecules Rubrene	1×10^{21}	3000-20,000	Moderate to Low	Moderate	Possible high payoff makes pursuit worthwhile
Monatomic Vapors Hg	1×10^{19}	1000	High	Low	Particularly severe laser problem
Diatomic Vapors I_2, IC1	2×10^{17} - 2×10^{22}	400-40,000	Moderate	High	Difficult spectroscopy but high payoff
- - Others					

* The availability of suitable 1 watt lasers is assumed.

Another man month could be well spent in assessing the potential of Sm^{2+}. The experiments are not difficult and the potential payoff is quite high, especially since a solid display medium could be quite suitable for a panel mounted cockpit display. The experimental program would consist of verifying the results alluded to in Pringsheim's book, and searching for the metastable excited state of Sm^{2+} in those hosts in which the ion exhibits visible fluorescence. Some time and/or money would, of course, have to be devoted to material preparation. This should not exceed the equivalent of a man month of effort.

The organic molecules represent an area with a high potential, but one in which the problems are relatively poorly defined. Modifications of the rubrene structure should be investigated as well as appropriate sensitization procedures. Calculations have not yet been done on a specific molecule and our state of knowledge is rather primitive. The decision to undertake a full experimental program should be preceded by two man months of preliminary measurements and calculations.

The preliminary work suggested for the organic molecules already has been done for I_2 and the results are quite favorable. A display of several hundred spots should be possible using I_2, and several thousand using ICl. The reason for including I_2 in the experimental program when we feel that ICl has a higher potential, is that the spectroscopy of I_2 is better known and its inclusion in the program will allow a more systematic procedure to be followed. The major component problem in a display utilizing the halogen molecules will be the two to three micron lasers which are expected to be required for the excited state pump. However, currently available parametric oscillators will be suitable for the experimental work, and the reasonably broad linewidths encountered in these molecules at room temperature should facilitate the development of lasers suitable for the display. Major effort should therefore be devoted to the study of these molecules at the present time.

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[4]Zito, R., Jr. and Schraeder, A. F., Applied Optics, Vol 2, p. 1323 (1963)

SECTION 5

5. BEAM DEFLECTORS*

5.1 CRITERIA

The function of the beam deflectors is to cause the outputs of the energy sources to arrive at the proper point of intersection within the display volume. There are a variety of physical mechanisms which may be employed to create the required deflection. They may be evaluated according to the following criteria.

5.1.1 Two-axis Operation

The system requires that each of the pump beams be able to be scanned in both azimuth and elevation. The deflector therefore must be intrinsically capable of two-axis deflection or it must be possible to cascade two orthogonally oriented, single-axis deflectors.

5.1.2 Random Access

The deflectors must be designed for random access rather than raster scan operation. The reason for this can be seen from the following example. Consider a display with 200 resolution elements per axis or 8×10^6 possible writing locations in the volume. Assume that 10^4 of these are being written in. If a raster scan is used and the display is refreshed 30 times per second, then each element is allotted 4×10^{-9} second per writing event. The laser pulses must therefore be synchronized to nanosecond accuracy which is not a reasonable requirement. In addition, since only a small fraction of the possible spot locations are being written in, either the laser must be pulsed irregularly or an attenuator must be used to block off the beam when an "empty" location is addressed. The irregular pulsing situation probably will result in unstable laser outputs. The use of an attenuator in the present example, will waste 99.9% of the laser light.

Random access operation, on the other hand, allows 3 μsec per writing event and regular laser operation with no waste of laser power.

A possible method for avoiding ghosts in the display volume would be to use a semi-raster scan. This would minimize the possibility of the excited state pump overlapping the region previously pumped by the ground state pump, but would require pre-sorting of the data.

5.1.3 Wavelength

The deflector must operate at the optical wavelength required by the display material. Some deflectors are exceedingly broadband. Others have a wavelength range which may be

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* Some of the information in this section was developed by Battelle Columbus Laboratories under sponsorship of the Air Force Avionics Laboratory under Contract Number F 33615-72-C-1484.

limited by absorption in the deflector or the power required to deflect the beam is a function of the wavelength.

5.1.4 Random Access Time

The number of events per second is MR, so the time per event is $[MR]^{-1}$. As indicated in Table 4-1, this time ranges from 5 msec to 0.67 μsec. In each case the random access time must be somewhat less than $[MR]^{-1}$ to allow time for the writing to occur.

5.1.5 Resolution

Again referring to Table 4-1, it can be seen that resolution of up to 300 resolved spots per axis is required.

5.1.6 Pointing Accuracy

The pointing accuracy should be considerably better than a spot diameter. There are two reasons for this. The first is that when angle deflection is used, angles intermediate to those defining the spot location centers on the entrance face, must be used to address locations deeper within the volume of the display. Second, and most important, is the requirement that the pointing accuracy be sufficient to guarantee good registration of the two pumping beams.

The registration problem has been investigated quantitatively by assuming two beams of Gaussian energy cross section. For orthogonal beams, the spot size and shape is independent of beam misregistration. The effect of misregistration on brightness is shown in Figure 5-1. It can be seen that the brightness is a rather insensitive function of registration. In general, pointing accuracies of 0.1 spot diameter should be quite sufficient.

5.2 DEFLECTOR TECHNOLOGY

5.2.1 Mechanically Driven Mirrors

Mechanically driven mirrors are the simplest of the available beam deflectors. They have the advantage of being essentially lossless, but suffer from a rather slow response time. Two basic types are available, galvanometer driven and piezoelectrically driven. Since the lowest natural frequency of a unit is some measure of its time response in random access operation, it is of interest to note that available piezoelectrically driven units have a lowest natural frequency of approximately 12 KHz compared to approximately 3 KHz for galvanometer units. For a 30/sec refresh rate, this corresponds to 400 and 100 spot maximum capability, respectively.

A complicating factor in the galvanometer drive is its susceptibility to hysteresis effects which in some units are as large as 4 percent. Since the higher response galvanometer units lack some internal means of position sensing to overcome the hysteresis induced error,

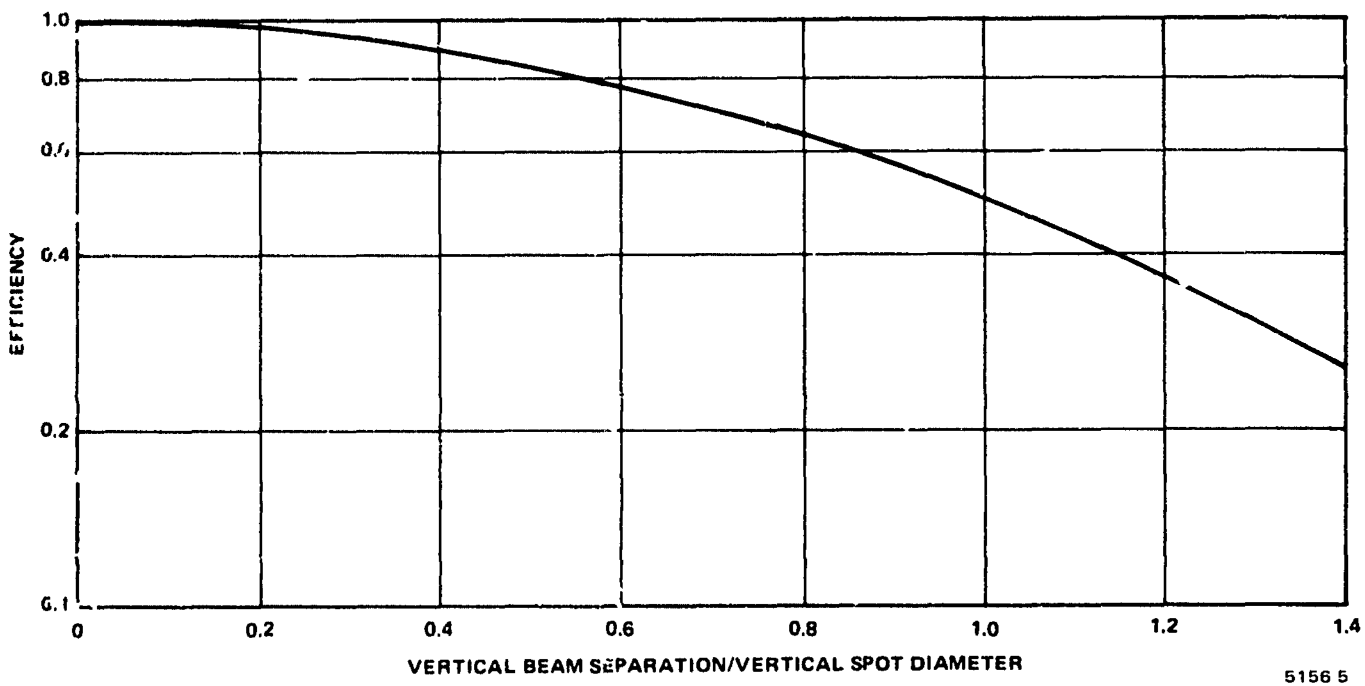

Figure 5-1. Relative Conversion Efficiency

Relative conversion efficiency (spot Brightness) for the orthogonal intersection of two gaussian pump beams as a function of the vertical separation of the beam centers.

it is necessary to always approach a newly commanded deflection angle from the same direction. This has the effect of reducing the hysteresis induced error to acceptable levels at the expense of nearly doubling random access time of the galvanometer drive. In the piezoelectric drive, this complication is circumvented by active position sensing.

Another usual characteristic of high response mechanical mirror drives is highly underdamped operation. This has the effect of producing slowly decaying oscillations about the mean orientation. The effect of such oscillation would be to enlarge the apparent size of the generated spot and decrease its boundary definition or cause misregistration. Since this would degrade the viewing characteristics of the display, additional damping would be required, decreasing the drive response.

5.2.2 Electro-optic Deflectors

Both analog and digital electro-optic deflectors are now under development. In the digital type [1] each stage is composed of a polarization switch and a birefringent element as in Figure 5-2. The switch chooses one of two orthogonal polarization states which have different paths in the birefringent crystal.

For a system with n spots per axis, there must be p binary stages where $n = 2^P$. Thus for a display with 256 spots/axis, an eight stage per axis deflector is required, so each beam must go through 16 deflection stages to effect two-axis deflection. The losses and the problem in cascading the two deflectors using such an approach may be prohibitive.

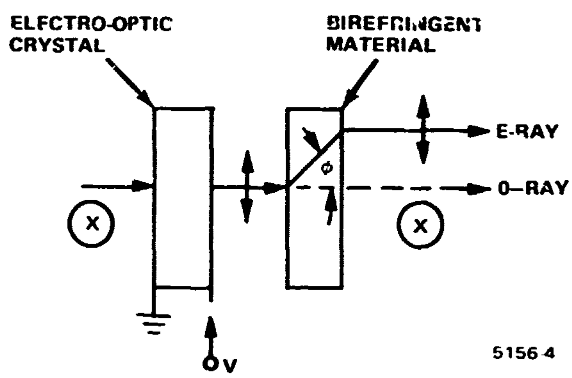

Figure 5-2. Typical Stage of a Digital Electro-Optic Position Deflector

One form of analog electro-optic deflector which has been successfully demonstrated [2] is illustrated in Figure 5-3. Through a series arrangement of electro-optic prisms, a light beam is deflected by varying the refraction index of each prism. The deflection of the prism is controlled by applying an electric field to its top and bottom electroded faces. Alternating the electro-optic polarity of the prisms allows all prisms to be excited from a single polarity

electric field providing alternate index variations. This configuration yields an output continuously controllable in position beam, in contrast to the discrete beam positioning capability of the previously discussed digital electro-optic deflector.

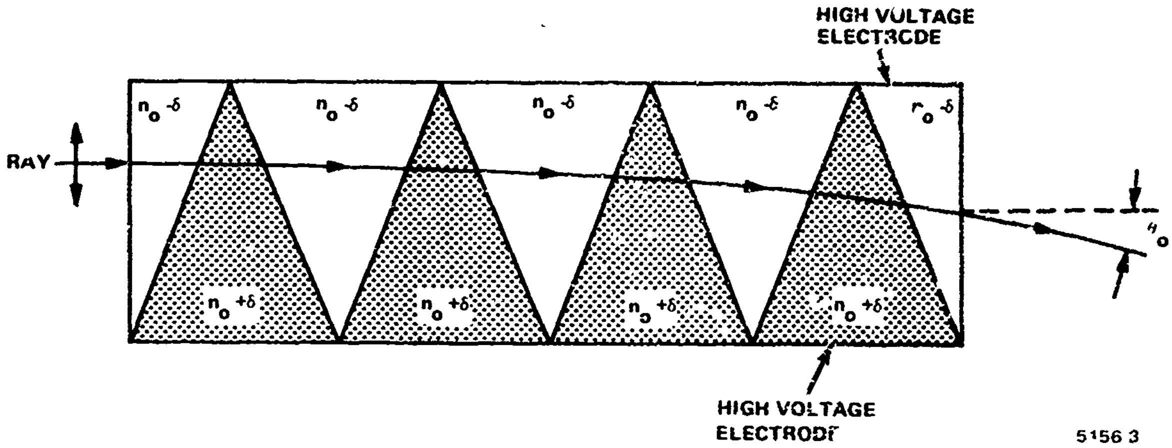

Figure 5-3. Refraction of a Light Beam Traversing an Iterated Electro-optic Angular Deflector

Both types of electro-optic deflectors have inherent limitations for SEF use. Although multistage digital deflectors have been built with resolutions in excess of 250 selectable beam positions and random access response of less than 10 microseconds, they are principally limited by relatively low optical transmission efficiency and the necessity for high-voltage drive electronics for each deflector stage. Similarly, better than 300-spot resolution has been demonstrated in the prism type of electro-optic deflector. Although the prism type of deflector exhibits a respectable optical efficiency of 60 percent, it suffers from high load capacitance. This both limits random access times and increases the complexity.

5.2.3 Acousto-optic Deflectors

Several types of acousto-optic beam deflectors (AOBD) are commercially available which are well suited for use in most of the SEF displays described in Table 4-1. The AOBD consists of an ultrasonic transducer bonded to a suitable transparent material. The transducer sets up an ultrasonic wave in the material which causes a periodic variation of the index of refraction of the acousto-optic medium. This so-called "phase grating" is used to diffract the incident light wave via the Bragg effect. The scattering angle is determined by the ultrasonic wavelength in the cell. The fraction of the incident light scattered is determined by the amplitude of the ultrasonic waves. The AOBD therefore may be used both as a deflector and as a modulator.

Deflector resolution and bandwidth are interrelated by

$$N_r = \frac{Td}{a} \Delta f, \qquad (1)$$

where T_d is the acoustic transit time across the optic aperature d, and Δf is the available

bandwidth of ultrasonic excitation. For uniform illumination of the deflector aperture $a = 1$, while for a circular Gaussian beam profile clipped at its $1/e^2$ intensity points, $a \approx 1.3$.

The close relationship between deflector resolution and the sonic transit time across the optical aperture, which is directly related to random access time, results in a tradeoff in AOBD design. Acousto-optic deflectors are commercially available for operation in the visible spectrum having random access times as short as 1 microsecond and resolutions of 100 equivalent Rayleigh spots. At the other end of the spectrum are commercially available units having resolutions of 575 spots and random access times of approximately 10 microseconds.

The fractional light intensity of the deflected beam I compared to the input beam intensity I_0 depends both upon acoustic power P_a and the wavelength λ of the light being deflected: [3]

$$\frac{I}{I_0} \sim \sin^2\left(\frac{1}{\lambda}\sqrt{Pa}\right) \qquad (2)$$

Light deflection efficiencies are a reasonably linear function of power up to 70 to 75 percent after which the nonlinearity of the $\sin^2$ function becomes important. Also, for deflection of longer wavelength optical beams, as indicated by equation 2, the acoustic power drive must increase as the square of the wavelength optical beams, as indicated to maintain the same deflection efficiency, all other things being equal.

As a consequence of the interdependence of power and wavelength, acoustic power drive must be increased for efficient deflection of infrared beams. Minimum deflection efficiencies of 50 percent are available currently in commercial cells of 400-spot resolution, over the infrared wavelength range up to 1.06μ. Cells suitable for deflection of beams with wavelengths as long as 2μ seem to be well within the bonds of existing technology. For longer wave wavelengths, the use of germanium as a deflector material is being explored.

5.3 SUMMARY

The acousto-optic beam deflector currently has capabilities sufficient to implement the first three displays in the hierarchy. The requirements of the 50,000 spot display will not be met by the current generation of AOBDs. To meet these specifications with a single AOBD, a deflector material with greatly improved characteristics will be required. If this material is not forthcoming, a cascaded system consisting of a AOBD for gross deflection and an electro-optic deflector for rapid character or short line generation could be considered. Such a system should be sufficiently fast to satisfy even the requirements of the 50,000 spot display. Of course, using the character generator to some extent will sacrifice complete random access operation but this should not be a serious problem.

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SECTION 6

6. ENERGY SOURCES

6.1 CRITERIA

The function of the energy sources is to excite a well defined spot in the display medium to the proper fluorescent level. To do this, the energy sources must satisfy a number of criteria. These will depend, to some extent, upon the specific display medium and the desired display characteristics. However, some general criteria can be used to define the energy source problem.

6.1.1 Wavelength

It is desirable to use pump beams which are not in the visible region of the spectrum. Furthermore, the number of undesirable processes which may occur will be minimized if the lowest possible photon energy is used. The lower limit is set by two factors. First, if two states are separated in energy by less than about 7 kT, there will be significant thermal population of the upper level which will lead to unwanted fluorescence. The wavelength corresponding to this energy (1400 cm^{-1}) is 7 microns.

A slightly more severe upper limit on the wavelength is set by the requirement that the output wavelength be sufficiently far removed from either of the pump wavelengths so that they may be easily separated by absorption filters. If a minimum value of 500Å is chosen, then the longest pump wavelength for a display emitting green light, must be less than 6.4μ. This will, of course, allow the other pump to be in the visible region. The requirement that neither pump be visible means that the shortest wavelength is 0.7μ, so for a green display the largest will be 2.4μ. The range 0.7μ to 2.4μ therefore is the ideal range. Wavelengths out to 6.4μ may be utilized if the concomitant disadvantage of having one visible pump can be tolerated. The specific wavelengths, of course, will be determined by the display medium.

6.1.2 Linewidth and Stability

The linewidth and wavelength fluctuation of the pump beams must be less than the width of the absorption line. Excessive spectral width will result in part of the beam being unabsorbed and therefore wasted. Lack of stability will result both in wasted energy and fluctuations of display brightness.

The minimum possible absorption linewidth is that due to the Doppler broadening of an atomic transition of a room temperature monatomic gas. This linewidth is given (1) by the expression,

$$\Delta\lambda_D = \frac{2\lambda_0}{c}\left(\frac{2RT\ \ln 2}{M}\right)^{1/2} \tag{1}$$

where λ_0 is the wavelength of the center of the line and c, R, T and M are the speed of light, universal gas constant, absolute temperature and molecular weight respectively. It can easily be seen that, for atomic mercury at room temperature a 2500Å absorption line will have a width of 2.2×10^{-3}Å. For molecular iodine, the Doppler width of an 3000Å line would be 6.2×10^{-3}Å.

The next broadening mechanism which must be considered is pressure broadening. Adding one atmosphere of argon to a room temperature mercury vapor 2 has the effect of increasing the linewidth of 0.02Å. Larger effects are expected in iodine or more complicated molecules with linewidths up to several hundred angstroms being observed in solids. Thus the minimum pump linewidth required will be on the order of 0.01Å, with larger values being acceptable for other materials.

6.1.3 Pulse Rate and Pulse Width

Pulsed excitation is desired both because it is the most efficient way to perform the sequential excitation and because there is a pause between pulses during which the deflectors can be switched to a new position. The required pulse rate is MR pulses/sec and obviously depends upon the specific display. Values of MR in Table 4-1 range from 200 to 1.5×10^6 per second.

The entire pulse sequence must be over in a time less than the shorter of τ_2 or $(MR)^{-1}$.

6.1.4 Optical Quality

The pump beams must be of sufficient optical quality to allow the formation of a spot by the SEE process at any point in the display volume with minimal variation in the spot size. If, as previously discussed, a minimum spot size of 0.5 mm is desired and 10% increase in this diameter is allowed over the display volume, then for a 2 mm diameter gaussian laser beam, a 1 meter lens will allow the use of a 20 cm display volume. This gives 400 resolvable spots which is a reasonable value for the upper limit of the display resolution.

The use of a beam of less than perfect quality (i.e., diffraction limited) will result in severe losses upon collimation and will limit the efficiency of several types of beam deflectors. It is possible to get a diffraction limited beam only from a high quality laser operating in or close to a single transverse mode (TEM_{00}).

6.1.5 Average Power

It is anticipated that, for an efficient display medium, one watt of pump power incident upon the medium will suffice for a high capacity display. The losses in the system should not exceed 50%, so a laser power of several watts should suffice. As the ratio of σ_{12} to σ_{23} becomes smaller, it can be shown that the maximum utilizable excited state pump power decreases. For a good display medium, I_{12} should be several watts while I_{23} is several milliwatts.

6.2 LASERS

It is evident from the preceding discussion that the energy source requirement can be satisfied only by a laser. Even if the beam quality problem could be solved, the linewidth and average power requirements combine to give a spectral power density which is in general unobtainable from any other type of source. The most useful lasers are those which can be tuned since it is unreasonable to expect coincidence between a power fixed-wavelength laser line and the specific wavelength required by a given display material. For completeness fixed wavelength lasers will be discussed briefly. The several classes of tunable lasers will then be dealt with individually.

6.2.1 Fixed Wavelength Lasers

In Table 6-1 are listed those laser lines which are commercially available with average powers greater than 50 mwatts and have wavelengths between 0.6μ and 3μ. Pulse rates of the gas lasers and cw-pumped solid state lasers ranging from cw to 10 MHz can be obtained by cavity dumping techniques.[3] In the table only one manufacturer was indicated for each laser although in some cases several sources are available. The ruby laser was not included since it is difficult to pulse rapidly.

Table 6-1. Potentially Useful Fixed-Wavelengths Lasers

Wavelength, micron	Power, mwatts	Type	Manufacturer
2.1	10,000	Ho:YAG	Hughes (AFAL)
1.[illegible]3	60	Nd:YAG	Chromatix
1.358	200	Nd:YAG	Chromatix
1.338	300	Nd:YAG	Chromatix
1.318	500	Nd:YAG	Chromatix
1.153	50	He-Ne	Spectra Physics
1.123	225	Nd:YAG	Chromatix
1.116	225	Nd:YAG	Chromatix
1.112	200	Nd:YAG	Chromatix
1.074	200	Nd:YAG	Chromatix
1.064	1,000	Nd:YAG	Chromatix
1.061	220	Nd:YAG	Chromatix
1.052	150	Nd:YAG	Chromatix
0.946	60	Nd:YAG	Chromatix
0.799	60	Krypton	Coherent Radiation
0.752	200	Krypton	Coherent Radiation
0.679	100	Nd:YAG	Chromatix
0.676	150	Krypton	Coherent Radiation
0.667	150	Nd:YAG	Chromatix

Table 6-1. Potentially Useful Fixed-Wavelengths Lasers (Contd)

Wavelength, micron	Power, mwatts	Type	Manufacturer
0.659	150	Nd:YAG	Chromatix
0.647	1,000	Krypton	Coherent Radiation
0.633	50	He-Ne	Spectra Physics

6.2.2 Parametric Oscillators

The optical parametric oscillator (OPO) is a device which utilizes the nonlinear polarizability of a noncentrosymmetric crystal to convert an incident laser beam into two beams at longer wavelengths. The successful operation of an OPO was first reported in 1965. Subsequent work resulted in extended tuning ranges and the demonstration of OPO action in materials other than the prototype material $LiNbO_3$. The OPO field is one in which a good deal of research is still being done. A very recent publication deals with a CdSe, OPO with outputs around 2.2μ and in the 9.8 to 10.4μ region with anticipated 2μ to 4μ and 8μ to 15μ tuning ranges.

The output wavelength λ_s of the OPO is accompanied by an idler at λ_i. These are related to the pump wavelength λ_p by

$$\lambda_s^{-1} + \lambda_i^{-1} = \lambda_p^{-1} \quad . \tag{2}$$

An additional constraint "for cumulative parametric interaction and thus significant gain is that the generated polarization wave at each of the three frequencies travel at the same velocity as a freely propagating electromagnetic wave". The angle of incidence of the pump beam and the temperature of the OPO crystal determine the specific wavelengths which satisfy these conditions. The OPO therefore can be tuned by angle or temperature variation.

Presently, only one commercial OPO manufacturer exists. The available OPO has a tuning range of 0.65μ to 3μ, but average powers are limited to less than 10 mwatts and pulse rates are limited to 1200 pps. The tuning range is limited by the characteristics of the OPO crystal ($LiNbO_3$) and the range of pump wavelengths available from the Nd:YAG laser used to pump the OPO. The power and pulse rate limitation arise from damage problems in the $LiNbO_3$ and from the characteristics of the Nd:YAG laser. Currently up to 30% optical conversion efficiencies are possible, and not much increase in this figure is anticipated. However, average powers of up to 1 watt are predicted within a five year time period, probably by increasing the size of the parametric interaction region and increasing the damage resistance of the crystals.

In the 1.7μ to 3μ range the current OPO bandwidth is about 0.004Å. If the average power and pulse rate of this device are increased as expected, it will make an ideal pump for the

SEF display. Its only drawback is the cost, which currently exceeds $40,000. This cost is expected to diminish over the next few years, although not to the extent which the price of simpler lasers have decreased in the five year period following their introduction. It is encouraging that many variations of the parametric oscillator are currently under investigation. New operating modes, [8] and additional materials such as $Ba_2NaNb_5O_{15}$ [9] and Li_2GeO_3 [10] are the subject of recent publications.

6.2.3 Dye Lasers

The first operational dye laser was reported in 1966.[11] Since then, an enormous amount of work has been done on various types of dye lasers, much more than has been done on optical parametric oscillator. A recent review [12] of the dye laser area contains a list of over a hundred references. This is by no means a complete list of the publications in the field.

The primary reason for the relative amounts of activity in the dye laser and OPO fields is that a useful dye laser can be built in a rather inexpensive, unsophisticated manner as opposed to the sophisticated engineering and expensive components required for the OPO.

The operation of the dye laser is depicted in Figure 6-1. The dye molecule is characterized by singlet and triplet manifolds. Pumping is effected by optical excitation of the $S_0 \rightarrow S_1$ and/or $S_0 \rightarrow S_2$ transitions. The output is always a transition between levels in the S_1 and S_0 manifolds. Since the electronic levels are broadened to several hundred angstroms by vibrational and rotational interactions, the normal $S_1 \rightarrow S_0$ fluorescence occurs over a wide bandwidth. Lasing action can be enhanced at a given wavelength in this band by putting a dispersive element in the laser cavity permitting only the desired wavelength to be amplified. Tuning is effected by adjusting this dispersive element.

The triplet levels have two deleterious effects. First, nonradiative decays from the S_1 to the T_1 level drain the upper lasing state. Second, and more serious, once the T_1 population becomes high enough, the lasing action is quenched since the $T_1 \rightarrow T_2$ absorption usually corresponds to the $S_1 \rightarrow S_0$ emission. A major advance in dye laser technology came when quenching agents were introduced to depopulate the T_1 level thereby allowing dye lasers to operate in a continuous as well as a pulsed mode.

There are currently a number of dye lasers and dye laser components commercially available. These are pumped in a variety of ways, and will be discussed in terms of their potential use in the SEF display in groups according to the excitation mechanism.

Flashlamp excitation of dye lasers is the least expensive and, in many ways, the easiest method of excitation. The prime requisite is that the flashlamp deliver sufficient energy to the dye at a high enough rate to overcome the rapid $S_1 \rightarrow S_0$ decay. Commercial systems are available which produce 1 to 2 mj/pulse at rates up to 50 pps. The major problem in using a flashlamp pumped dye laser in the SEF display is that no major increase in the pulse rate seems likely.

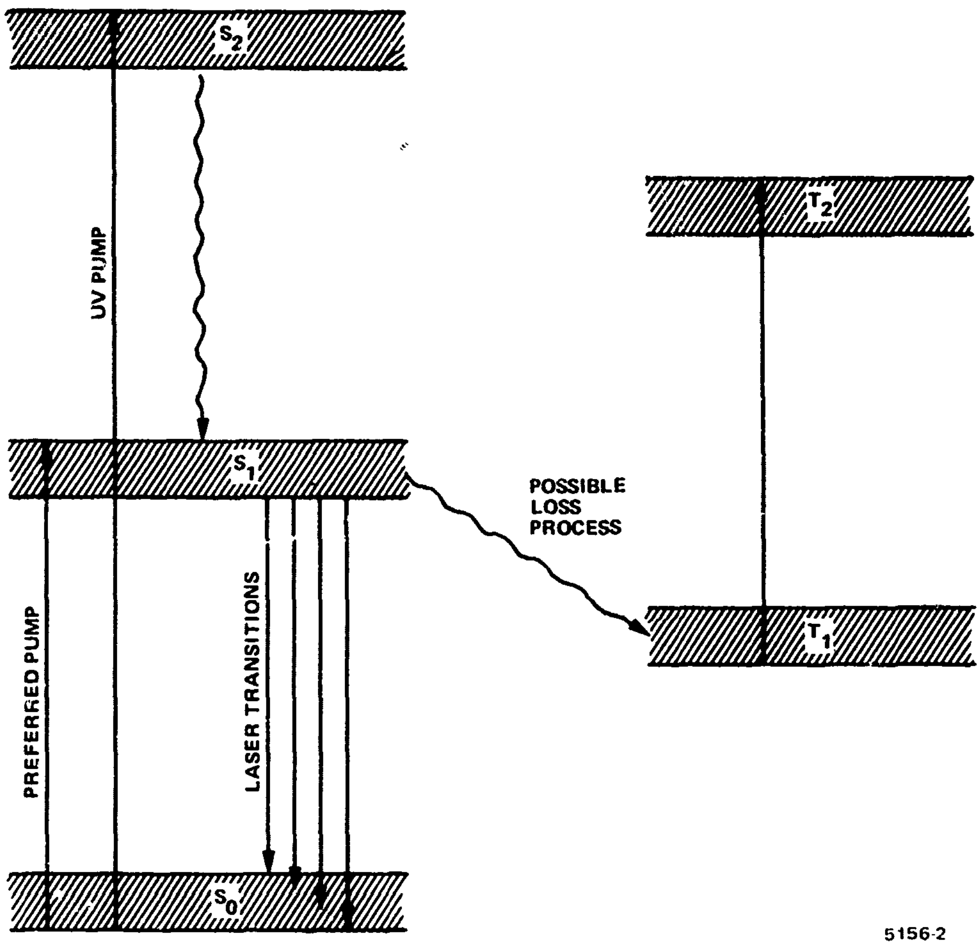

Figure 6-1. Energy Level Diagram of Typical Laser Dye

The obstacle to high pulse rates ultimately boils down to a heat dissipation problem in the flashlamp/dye-cell system. Even if we allow a tradeoff between energy per pulse and pulse rate, keeping the average powe constant, the problem remains since a reduction in energy pc" pulse is achieved by reducing the flashlamp and dye-cell size and consequently their heat dissipation capabilities. Maintaining a large laser size and running at low energy outputs is very inefficient since the threshold energy still has to be overcome for each pulse.

A possible way around this problem is to pump continuously and pulse the dye output by other means. The cw pumping technique has been discussed [13] but has not been achieved with incoherent pumps.

Another limitation on high flashlamp pulse rates has been pointed out.[14] In order to get high-performance, high-brightness lamps, the internal gas pressure is critical. At the required pressures the recombination time after pulsing is about a millisecond. Pulse rates exceeding 1000 Hz are therefore not possible with these lamps.

There are several reasons for preferring to pump dye lasers with other types of lasers rather than with flashlamps. The repetition rate and rise time problems can be overcome with a number of Q-switched or possibly with mode-locked lasers. In addition, the spectral purity of the laser output makes it possible in many cases to pump directly into the proper absorption band of the dye. In general, pumping with a wavelength several hundred angstroms shorter than the dye output is the preferred mode of operation. However, by utilizing the uv absorption band (generally $S_0 \rightarrow S_2$ of many dyes, the N_2 laser (3371Å) has been used to pump dye lasers which completely cover the range from 3600Å to 6500Å. In addition, it has been shown [15] that by introducing suitable mixtures of dyes into the laser cavity, this range can be extended to longer wavelengths. This is accomplished by utilizing the transfer of excitation from a uv absorbing dye to a dye which does not absorb at the pump wavelength, but where absorption band overlaps the fluorescence band of the first dye. Pulse rates of the N_2-laser pumped dye laser are currently limited to 500 pps by the pulse rate of available N_2 lasers.

The ruby laser also has been used to pump a wide variety of dyes. Because of its longer wavelength (6943Å as compared to 3371Å for the N_2 laser) the ruby is capable of pumping dyes whose output extends into the near infrared region. However, the use of the ruby laser as a dye pump is again not suitable for the SEF display because of pulse rate limitations.

A more promising approach, especially at wavelengths exceeding 1 micron, is to use the solid state neodymium laser as a pump. Excitation with a Q-switched Nd: glass laser (output at 1.06μ) has resulted [16] in lasing over the range 1.0810μ to 1.1815μ using a variety of dyes. The Nd: YAG laser is capable of much higher pulse rates than the Nd: glass laser, which means that a usable system, tunable in 1.1 to 1.2μ range, should be possible.

As a result of increased understanding of the fluorescence properties of the dyes and better optical cavity construction techniques dye lasers have been built with greater efficiency and improved operating characteristics. As a result of these advances, continuous operation of a dye laser was achieved in 1970 [17] using a 1 watt argon laser to excite the dye.

Dye lasers have several advantages for use as sources for the SEF display. The optical quality can be made quite high and the linewidths can be narrowed to less than 0.01Å. In addition, they probably can be pulsed at high rates by using a cavity dumped argon ion laser or by using a cw ion laser and mode locking the dye laser. [18] Mode locking produces pulses at the rate of c/2L where L is the cavity length, and is therefore suitable only for very high pulse rates.

Dye laser wavelengths are available up to about 1.2μ, and it is probably unreasonable to expect dye lasers with outputs at much longer wavelengths in the near future. In fact, the upper wavelength limit of laser dyes is expected to be about 1.5μ [19] due to the rapid transfer of energy from excited electronic states to molecular vibrations. On the other hand, better pumping techniques for near IR dyes can be anticipated. It should be possible to use the 0.647μ output of the krypton ion laser to pump dyes which emit in the 0.7μ to 0.85μ region, just as the 0.5145μ argon line is used to pump 0.58μ to 0.70μ dye lasers. There is even the

possibility of pumping with the 0.752μ krypton line to get further into the IR. Another possibility, which should result in a compact tunable laser with a very high overall efficiency, is to pump with an array of LED's whose output is chosen to match the absorption band of the dye.

Dye laser systems can be used to generate coherent radiation outside the emitting region of the dye by employing a variety of nonlinear optical effects. Frequency doublers can be used to extend the dye laser range into the uv. To generate tunable IR using visible dye laser outputs, Dewey and Hocker [20] mixed the tunable laser radiation with the fixed wavelength pump in a $LiNbO_3$ crystal. They were able to tune the difference frequency in the 3 to 4μ region. Another approach suggested by Herbst [b] is to use the dye to pump a parametric oscillator to get tunable radiation in the 0.7 to 1.6μ range. Progress in many of these areas is expected in the next few years.

6.2.4 Other Lasers

The parametric oscillator and the dye laser are the only commercially available tunable lasers which are potentially useful as energy sources for the SEF display. However, a number of other types of tunable lasers should be mentioned because of their potential application in the future.

There are a variety of semiconducting lasers with outputs in the near infrared region. The lasing action occurs in a very narrow junction region and, until recently, the output was characterized by being diffraction limited perpendicular to the plane of the junction and some two orders of magnitude worse than diffraction limited in the plane of the junction. This very poor optical quality made the injection lasers unsuitable for use as an SEF display pump. An advance in diode laser technology which may remedy this situation was the recent achievement [21] of single mode operation of a GaAs laser by placing the active material in a well designed optical cavity. The diode laser now may be thought of as a potential SEF pump in the 0.7 to 0.9μ range.

There are also a variety of Raman lasers which may prove useful. These are devices which have the ability to effectively shift a portion of the energy of a pumping laser to longer wavelengths. The amount of the shift is determined by the amount of energy absorbed by the Raman material during the process of being driven from its initial state to a different discrete higher-energy state. Raman laser technology is not yet sufficiently well developed for its potential to be estimated. However, it has been shown that spin-flip Raman laser [22] pumped by a CO_2 laser could be tuned over the range 10.9 to 13μ by varying the magnetic field in which the laser was situated.

6.3 SUMMARY

The light source situation might best be summarized by saying that each of the criteria previously discussed may be satisfied individually or possibly in pairs by some particular laser, however, that there are only a few discrete wavelengths at which all of the criteria can be simultaneously met. It is anticipated that should the need exist, all of the criteria

except average power currently could be satisfied over most of the dye laser wavelength range (0.5 to 0.7 micron). Furthermore, this range should be extended out to 1 micron or longer wavelengths within the next few years. Average powers of several hundred milliwatts are within reason.

The OPO is the only broadly tunable source which currently has an output at wavelengths beyond one micron. Its average power will certainly be increased beyond the present 10 milliwatts within the next few years. It is not clear whether its pulse rate will be pushed much beyond several thousand pps. It must be pointed out however, that in addition to the tunable dye laser-heterodine system mentioned previously there is a variety of less broadly tuned lasers available in the infrared .

The continuing progress in the laser field makes accurate prediction of the state of the art very difficult. Due to the diversity of approaches possible, the best tactic for the development of the SEF display is to look for better display materials. Then if the materials are good enough to warrant the effort, the specific lasers required by with these improved materials should be developed.

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SECTION 7

7. SUGGESTIONS FOR FUTURE DEVELOPMENT OF THE SEF DISPLAY

Although the attainment of the 50,000 spot system will require advances in the state of all three of the major display system components, the key to any major advance lies in the discovery of improved display materials. This becomes evident from a brief consideration of the range of Z-values involved from going from the present state of the art to the 50,000 spot display.

Currently using $CaF_2:Er^{3+}$ as the display medium and 100 milliwatt lasers at the appropriate wavelengths a 10 to 20 spot system having a Z-value in the 10^{13} to 10^{14} range can be constructed. To attain the $Z = 10^{22}$ goal some eight orders of magnitude improvement are required. For reasons of safety, size, power consumption, and to keep within presently accepted bounds of reality, we are seeking 1 watt lasers for the final system. Therefore, according to equation 3-13 we can expect to attribute only 2 orders of magnitude increase in Z to laser improvements. On the other hand, as has been discussed at the end of the Display Medium Section an 8 or 9 order of magnitude increase in Z by virtue of the discovery of improved materials is within reason.

Therefore it is evident that progression through the hierarchy must be lead by advances in the efficiency in the display medium which, of course, requires the discovery of better display materials. The projected development is predicted in Figure 7-1. The bench model based on 1971 materials will be constructed after a suitable delay for the completion of the system engineering work. Further limited advances may be achieved through additional laser development. In Figure 7-1 sufficient effort in the materials area is assumed so that significant advances in the materials will be made in 1973 and 1975. In order to capitalize on these advances, some time must be allowed for the construction of appropriate lasers. However, the long system engineering effort probably will not be required for later systems because of the experience gained during the construction of the bench model. Finally, for the achievement of the ONR goal system a suitable length of time has been left for the final deflector development. As can be seen, assuming a sufficient rate of effort, this system is predicted for 1978.

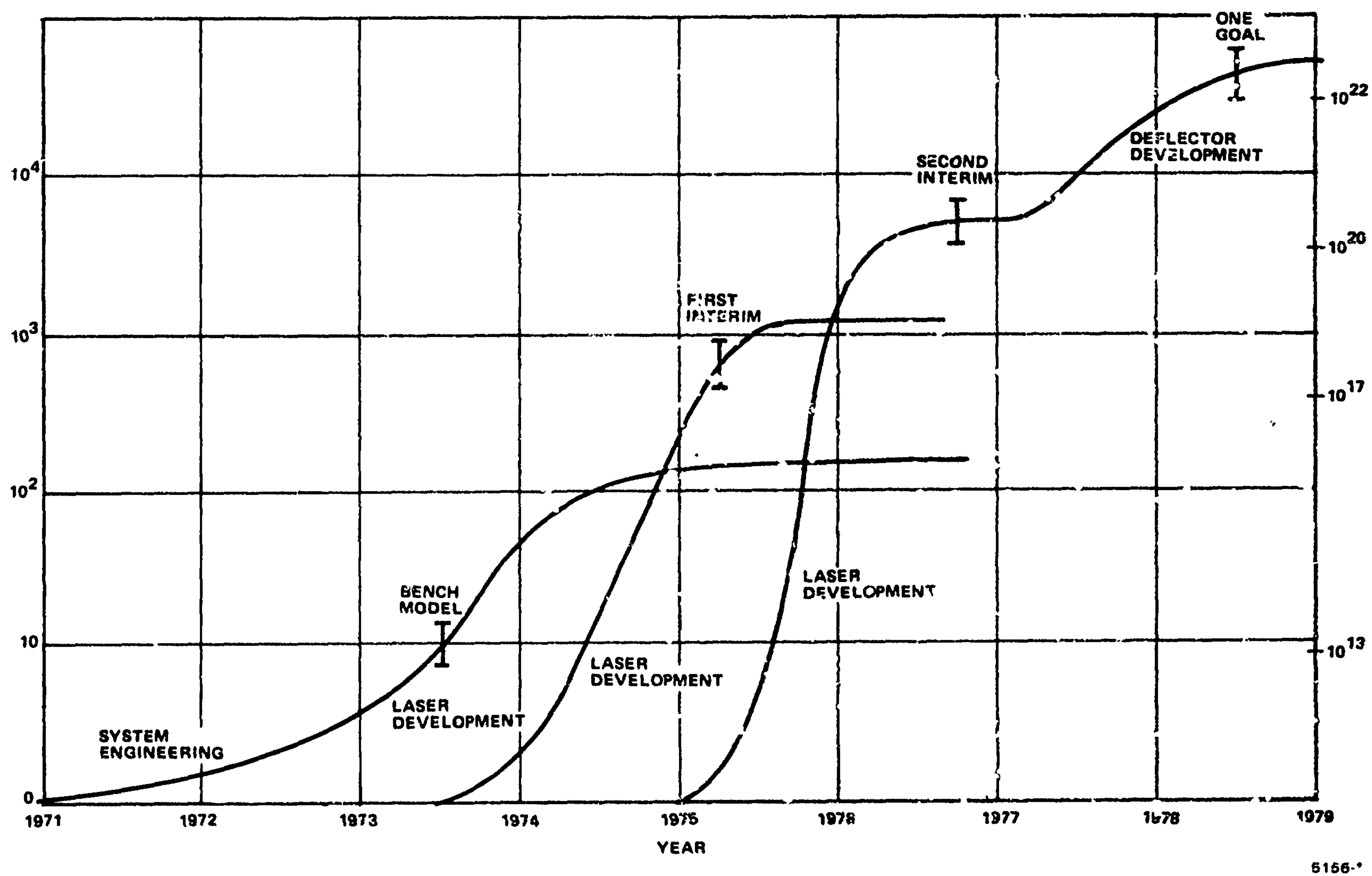

Figure 7-1. Projected Display Development

INDEX

Definition of Terms

t	=	time (sec)
F_{31}	=	(Brightness of Display Element (Photons/cm^3 per sec)
F'_{31}	=	Output of Display Element (Photons/sec)
M	=	Number of Simultaneously displayed spots
R	=	Refresh Rate (sec^{-1})
L	=	Display Length (cm)
r	=	Radius of Display Element (cm)
I_{ij}	=	Pump Intensities (photons/cm^2-sec) (states i to j)
σ_{23}	=	Absorption cross-section for excited state pump
η_{31}	-	Fluorescence quantum efficiency.
τ_2	=	Lifetime of the first excited state
N	-	$\sigma \Sigma n_i L$ total molecular concentration of active medium, (CM^{-3}) in general $n_1 \approx N$
n_3(min.)	-	Minimum fluorescence center concentration n(min.)
Spot Radius		
d	=	Spot dia (cm)
B	=	Spot brightness (ft - L amberts)

σ_{ij} = absorption coefficient $i \rightarrow j$ (states)

A_{ji} = radiative decay rate ($j \rightarrow i$) (sec^{-1})

R_{ji} = nonradiative decay rate (sec^{-1})

Z = Characteristic display parameter a measure of display capability

V_{λ} = Visual spectral sensitivity coordinate

h = Planks constant

$\gamma_{(nu)ij}$ = Freq (Hz) of optical radiation

λ_{ij} = Wavelength of optical radiation